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METEORITES ARE INTERPLANETARY SPACE PROBES

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ABSTRACT. The results of investigations made in special laboratories of 25 meteorites that have fallen in the past 15 years are given. The role of meteorites as interplanetary space probes is explained and the manner in which meteorites have provided the boundary between the galactic and solar magnetic fields is discussed.

Spacecraft and automatic interplanetary stations have provided a great deal /10* of information on the interplanetary medium in recent years. Yet not one of the artificial satellites has provided information on the region of the solar system beyond the orbit of Mars or on the asteroid belt. Yet it evidently is in this region where the transition from a specifically circumsolar medium to the common medium of that arm of the galaxy in which the solar system is immersed takes place. The only objects that visit this region and then fall on the earth are meteorites. The many years of work done by the author of this article, and her co-workers, "forced" the meteorites to yield some information on this interesting, and still enigmatic, region of the solar system.

A modern model of the interplanetary medium suggests the dynamics of the picture, changing in time and in space, of the movement in the direction from the sun of the magnetic field inhomogeneities, of the unique "magnetic clouds." Investigation of interplanetary space by space rockets has resulted in exposing interesting features of the distribution of interplanetary magnetic fields. It appears that interstellar gas, galactic cosmic rays (a flux of fast charged particles), and the galactic magnetic field are continuously entering the solar system. This is the result, in particular, of the solar system being inside one of the spiral arms along which the galactic magnetic field moves. Also learned was the fact of the existence of a continuously acting mechanism, pushing the interstellar gas and the galactic magnetic field far out to the edge of the solar system. This phenomenon was understood for the first time when observing

* Numbers in the margin indicate pagination in the foreign text.

comet tails that form as a result of the gas flowing out of the nucleus of the comet being pushed radially away from the sun.

The result of numerous investigations, from the earth, as well as right in space, has been to establish that interplanetary space is filled with hot plasma flowing continuously from the solar atmosphere. This is the solar wind, moving in all directions from the sun at supersonic speed, 330 - 800 km/hr. The outermost shell of the solar atmosphere, the solar corona, is the source of the solar wind. It was thought that the reason for the escape of the gases was the very high kinetic temperature of the solar corona (some 1.5 million degrees). It now has been settled that the speed of the solar wind changes with solar activity, and is minimum during a quiet sun period.

Solar plasma in interplanetary space, despite its rarefaction, has comparatively high electrical conductivity, sometimes ten thousand times that of the electrical conductivity of sea water. It is this electrically conducting medium, moving at high speed, that attracts the galactic magnetic field and extends it to the outskirts of the solar system. But it is curious indeed that interplanetary space, particularly the region between Venus and Mars, never is without magnetic fields. The first of the space probes, Venera 1 and Pioneer V, /11 revealed that this space is filled with strong magnetic fields ranging in intensity from a few to 10 - 20 γ ($1\ \gamma = 10^{-5}$ Oe).

Subsequent investigations led to the conclusion that these fields, within the limits of the solar system, possessed a spiral structure. E. Parker, in 1958, explained how this structure comes about. According to his theory, the gases, escaping radially because of the sun's rotation, actually will be positioned along some curved line, at each point along which the speed sector will hold its radial direction (Figure 1). Magnetic fields, as if frozen in the plasma of the solar atmosphere, are carried away from the solar corona. The interplanetary magnetic field, therefore, is a magnetic field, carried away from the sun by the solar wind and frozen in the solar atmosphere [1].

The active regions of the sun, characterized by magnetic fields significantly stronger than those in adjacent regions, play a tremendous part in the process of gas escape from the solar atmosphere. Magnetic regions, hundreds of thousands of kilometers in extent, have been observed on the surface of the sun,

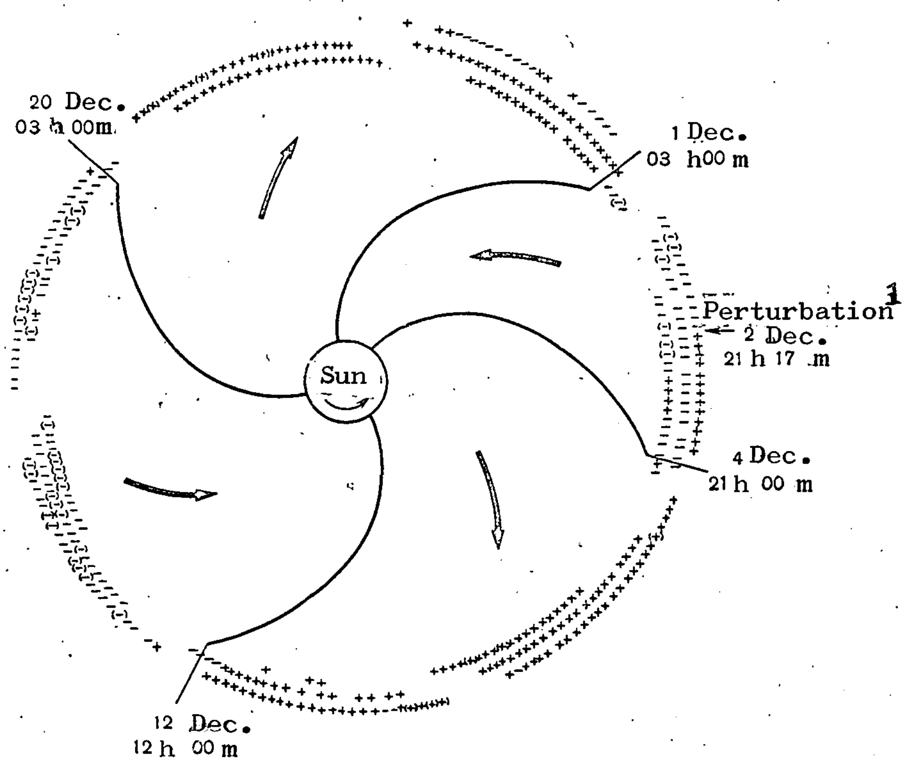

Figure 1. Sectorial structure of solar magnetic fields. The heavy arrows indicate prevailing field direction in the sectors. The crosses indicate the direction of the field from the sun to the point of measurement, the dashes the direction toward the sun. The three circles of these symbols correspond to three revolutions of the sun. The dates around the periphery refer to the first revolution (the outer circle). Measurements were made between 27 September 1963 and 15 February 1964.

the photosphere, for example. The field intensity in these regions is several oersteds, lasting from a few months to 18 months. The facular plages, the very bright filament formations in the solar atmosphere, are closely associated with the magnetic regions [2]. The facular plages are very irregular, complexly structured, formations on both sides of the solar equator to latitudes of 50 - 55°. They range in size from a few to hundreds of thousands of kilometers. The brightness of the facular plages increases with increase in the intensities of the magnetic regions with which they are associated. Dark, irregularly shaped formations, sunspots [3], often are observed in the facular plages. These large, cold, disk-shaped depressions are gigantic electromagnets with a field intensity greater than 1000 oersteds. Sunspots usually appear in groups 5 - 15° on either side of the equator. They last from a few hours to several months. Spots usually are a few thousand kilometers in size.

Solar flares occur most often in the vicinity of facular plages. These are brief explosive processes accompanied by the sudden appearance of radiation lines of hydrogen, helium, calcium and other elements in the optical spectrum, of blasts in the r-f region, and of intensification of X-ray emission. The most spectacular are the proton flares, accompanied by the emission of solar cosmic rays. The first solar cosmic ray flares were recorded on earth on 28 February 1942. They have been given a great deal of attention since that time [4].

A detailed investigation of solar cosmic rays and of the solar wind has revealed that the magnetic field lines of force make one complete revolution every 6 AU[1] in years when solar activity is a minimum, so the structure of the magnetic field in interplanetary space should be sectorial, and this has been confirmed by direct measurements by space rockets (Figure 1). The solar wind /12 propagates radially from the sun, in a manner similar to the movement of water emitted in the form of a curved stream from a rotating sprinkler.

Magnetic Barrier for Solar Cosmic Rays

The situation in interplanetary space during the quiet sun years is such that galactic cosmic rays are free to penetrate the region near the sun. A. N. Charakhch'yan and T. N. Charakhch'yan have demonstrated that the intensity of galactic cosmic rays at the boundary of the earth's atmosphere was 0.39 particles/cm^2 · sec · sr at the minimum of the preceding, 19th, solar cycle (1965).

There is a significant change in the situation during years of intense solar activity. An intensive flux of solar cosmic rays appears in the interplanetary space. Their greatest intensity in the past 30 years was observed during the 23 February 1956, flare, at which time the flux of low-energy particles at the boundary of the earth's atmosphere increased by a factor of 1000. Interesting enough, the increase in the flux of solar cosmic rays was very rapid, the decay quite slow. Moreover, immediately after the flare the flux of solar

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1 One astronomical unit (AU) is the mean distance of the earth from the sun, approximately equal to 150 million kilometers.

cosmic rays on the earth had a definite radial direction from the sun, becoming isotropic after some time. This suggests that solar cosmic rays are bent and reflected, encountering in their path magnetic inhomogeneities formed by solar magnetic fields ejected from the active regions during a flare (Figure 2). The occurrence of these inhomogeneities is the result of the nonuniform structure of magnetic fields in the solar atmosphere. Moreover, the speed of the solar wind depends greatly on the heliographic latitude and longitude, and on the time that has elapsed after the flare.

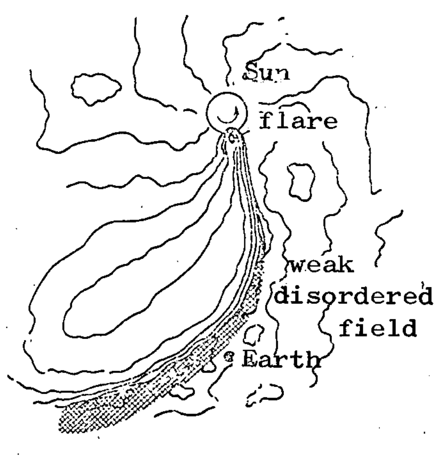

Figure 2. Magnetic inhomogeneities in interplanetary space during the 12 November 1960 solar flare. Shown are the magnetic lines of force sometimes closing in space (frozen fields). The cross-hatching designates the flux of cosmic rays emitted during the flare.

Observations [5] have revealed that there are cases when the decay in the intensity of solar cosmic rays occurs in accordance with an exponential law. This was observed for the first time during the 4 May 1960 flare, but a similar effect was observed later on, during other flares as well. The shape of the energy spectrum of the solar cosmic rays remained constant with respect to time during the most powerful of the flares, that of 23 February 1956. What all these facts tell us is that the solar cosmic ray diffusion region is limited, and does not exceed a few astronomical units. In 1962, C. MacCracken suggested the existence in interplanetary space of a sharply defined magnetic barrier 2.5 AU (375 million kilometers) from the sun, that was reflecting solar particles.

An additional argument in favor of the existence of a magnetic barrier is the 30-minute delay in the beginning of the observation of the effect of the 15 November 1960 flare at stations at the time on the earth's dark side, as compared with the stations on the day side. The solar cosmic rays from the sun fell directly on the day side, but in order to fall on the dark side the rays had to once again reach the barrier, be reflected from it, and then set out on the return path to the earth.

All recent observations are persuasive in showing that an almost motionless "buffer" layer is formed 2 - 2.5 AU from the sun during intense solar activity between the supersonic solar wind and the interstellar medium (Figure 3). The solar wind changes from supersonic to subsonic in this region, and the magnetic field becomes irregular, turbulent. A great many magnetic inhomogeneities are forced into the "buffer" layer during a period of intense solar activity, and these slowly dissipate in interstellar space during years when solar activity is at a minimum.

Modulation of Galactic Cosmic Rays

Study of the intensity and energy spectrum of galactic cosmic rays during the 19th solar cycle (1954-1965) at the boundary of the earth's atmosphere, and in the region between the orbits of Venus and Mars, resulted in the development of extraordinarily interesting features of their variations with time. First of all, it developed that significant change occurs in the intensity of galactic cosmic rays in this region of the solar system. The greater the number of solar flares, the less the intensity of these rays. We know the number of sunspots, as well as other types of solar activity, change on an average eleven year cycle. The intensity of galactic cosmic rays changes on this same cycle [6] (Figure 4). This phenomenon, called the 11-year modulation of galactic cosmic rays, is the result of the action of the solar wind with frozen magnetic fields. Convection /13
flows, the result of the drift of particles from the sun caused by magnetic fields and electric fields induced by them, occur, and these sweep the low-energy particles of galactic cosmic rays to the outskirts of the solar system.

Characteristic of the 11-year modulation of galactic cosmic rays is a clearly shown dependence on particle energy. Intensities vary by almost a factor of 10 in the case of particles with an energy of 100 million eV, and by but a few percent in the case of particles with energy greater than 10 billion eV.

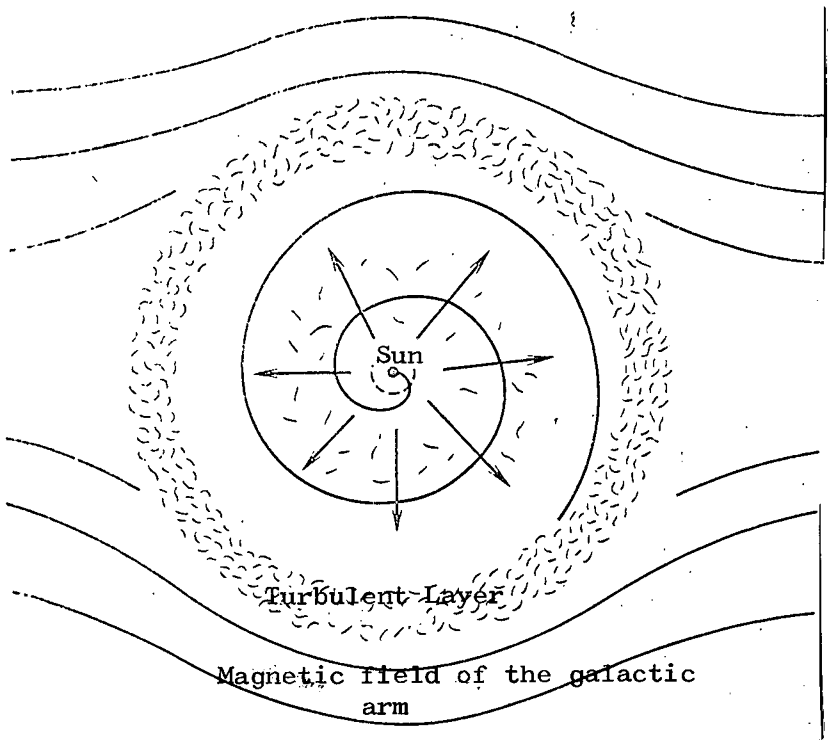

Figure 3. Schematic representation of the structure of the magnetic field in interplanetary space. The radial arrows show the direction of the solar wind. The spiral line is the solar magnetic field. Neither the solar wind nor the solar magnetic field can freely penetrate the turbulent layer. Outside this layer the magnetic field of the galactic arm predominates and here the galactic cosmic rays are not modulated by the 11-year cycle.

This effect is particularly evident during the period of maximum solar activity, and practically disappears during the period of the minimum. Yu. I. Storozhkov and T. N. Charakhch'yan discovered that during the years of the 19th cycle, the 11-year modulation of the intensity of galactic cosmic rays depended not only on the number of sunspots, W (or number of groups of spots), but on their middle heliographic latitudes as well. This has been confirmed by analysis of data on the first half of the 20th cycle.

The number of particles with energies greater than, and less than, 1.5 billion eV is approximately equal in years of minimum solar activity, whereas in years of maximum activity the number of particles with energy less than 1.5 billion eV is negligible. Slow galactic particles cannot "break" through the magnetic barrier.

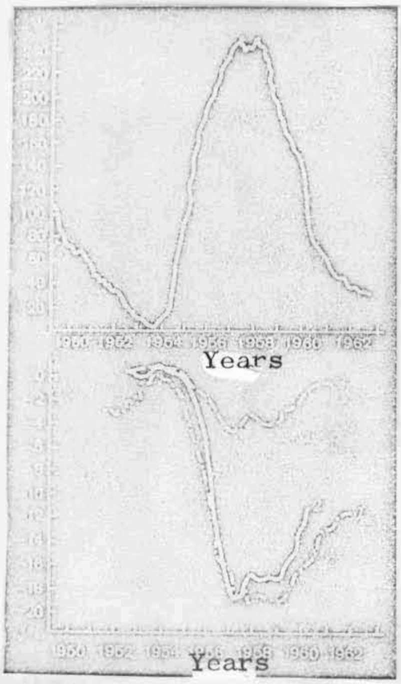

Figure 4. Upper. 11-year variation in solar activity. The absolute number of sunspots, W, is plotted on the ordinate. Lower. 11-year variation in intensity of galactic cosmic rays. Relative intensity, J (in %), is plotted on the ordinate. Only high-energy particles pierce the earth's magnetic field to reach the surface at the equator. Low-energy particles reach the poles. Hence, curve 3, plotted for a station on the equator, is characteristic of the variation in the flux of particles with energy greater than 15 billion eV. Curve 2, plotted for the middle latitudes, is characteristic of the variation in the flux of particles with energy greater than 3 billion eV, and curve 1, plotted for the high latitudes, shows the variation in the total flux of galactic cosmic rays of all energies. The solar wind cannot hold the high-energy particles, so curve 3 dips slightly with increase in solar activity. Low-energy particles are almost entirely swept out of the vicinity of the earth during a period of intense solar activity, with the result that the intensities of the fluxes represented by curves 2 and 3 will undergo sharp changes in different years.

Restoration of the intensity of galactic cosmic rays after a period of maximum solar activity occurs with substantial "protraction," the length of which is longer the lower the particle energy. There is a time interval (8 to 10 months, approximately) between the beginning of a new cycle of solar activity and the beginning of the decay in the intensity of the galactic cosmic rays. The beginning of the 20th cycle of solar activity, for example, was mid-1964, but the beginning of the reduction in the intensity of galactic cosmic rays was mid-1965. This phenomenon, discovered by J. Simpson, is called hysteresis (lag).

What is the explanation for all these features, and what is the extent of /14
the region in which these effects, associated with solar activity, occur? For one can be quite confident in suggesting that these effects ought not exist at very great distances from the sun.

Galactic Cosmic Ray Modulation Region

Assembled facts confirm the validity of the conception of the nature of those processes resulting in modulation of galactic cosmic rays. Nevertheless, many of the details of the modulation picture are not clear. Further work is required on the theory proposed by E. Parker back in 1956. The question of the size of the modulation region has remained an open one until quite recently. There are great discrepancies in the estimates made by different researchers. L. I. Dorman's data, based on observations of the lag in the change in the intensity of galactic cosmic rays in terms of level of solar activity, and on calculations of the equilibrium between solar plasma pressure and the external galactic magnetic field, provide a modulation region of some 100 AU (15 billion km). Other researchers (J. Gallaher, J. Simpson, A. N. Charakhch'yan, T. N. Charakhch'yan, and others) have used the radial gradient of galactic cosmic rays, based on space rocket measurements, or analysis of short-range large changes in their intensity at the boundary of the earth's atmosphere associated with changes in the characteristics of solar activity, to conclude that the modulation region certainly is not larger than 10 AU. In 1960, E. Parker suggested that the 11-year modulation of galactic cosmic rays can be attributed, in part, to the shock front in the region of the magnetic barrier, that is at a 2 - 3 AU distance. G. F. Krymskiy, in 1968, justified the concept that the primary role in the 11-year modulation was played by the region in which the solar wind becomes subsonic. His estimates show that the available data satisfy shock wave radius values of from 2 - 5 AU.

All these estimates are based primarily on the delay in change in electromagnetic conditions in interplanetary space with respect to the process on the sun causing them. Actually, the degree of lag is determined by the size of the modulation region, or, more precisely, by the time of movement of the solar wind causing modulation of galactic cosmic rays from the sun to the boundary with the galactic magnetic field. The great difference in estimates of sizes of the modulation region can be attributed primarily to the fact that the researchers use different parameters of solar activity to determine solar wind strength, for it remains to be established which of these parameters most completely characterizes solar wind speed and intensity.

Meteorites Are Interplanetary Space Probes

Investigation of the content of radioactive isotopes in meteorites provides a completely independent method for determining the dimensions of the modulation region, stripped of the ambiguities cited. Meteorites are unique natural bodies that each year fall on the earth's surface and contain within their composition and structure traces of many cosmic events that have taken place in the solar system [7]. Hence they are of exceptionally great scientific value, and are studied with the aid of the entire arsenal of modern methods. Meteorites are the only objects enabling us to make a direct study of the variation in the intensity of galactic cosmic rays over a period of several billion years and at a distance of several hundred million kilimeters from the sun. This is so because meteorites, during the time they move around the sun in an elongated orbit (Figure 5), gather into their composition the most varied of radioisotopes resulting from nuclear reactions caused by particles of galactic cosmic rays. Measurement of the radioactivity of the isotopes provides total intensities of galactic cosmic rays for the period of time corresponding to the lifetime (one and one-half times the half-life) of the radioisotopes, that is, from a few days to several billion years before the meteorite fell to earth.

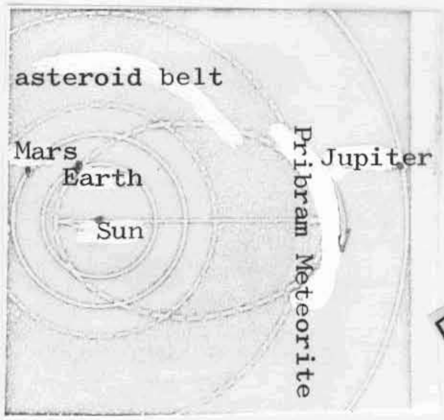

Figure 5. Orbit of the Pribram meteorite that fell on Czechoslovakia on 17 March 1959. This is the first meteorite, the movement of which in the atmosphere could be photographed from several different geographic points, and thus provide the means for calculating its orbit. The pribram meteorite was in the asteroid belt and beyond, where modulation of galactic cosmic rays takes place, for most of the time.

So it is that each falling meteorite is a unique space probe carrying invaluable scientific data on conditions in interplanetary space.

Approximately 25 meteorites have been observed to fall in the past 15 years, and all have been carefully investigated in special laboratories. /15 Efforts have been made to obtain data on the intensities of galactic cosmic rays for different time intervals. But there remains a significant indeterminacy because of a lack of methods to use to establish the precise value of the rate of formation of the various isotopes in nuclear reactions for each meteorite of a definite size and chemical composition. The author, and her co-workers, have spent many years investigating the answer to this problem by modeling nuclear reactions in meteorites. Targets of different chemical compositions, corresponding to the composition of meteorites, have been irradiated with protons with energies of from 100 million to 20 billion eV, accelerated in giant accelerators in the Combined Institute for Nuclear Research (Dubna) and in the European Center for Nuclear Research (near Geneva). The result of these experiments has been to find a relationship between the probability of the formation of isotopes and the energy of the bombarding particles and the mass number for the target element.

However, in addition to this, in order to study the effects of nuclear reactions in meteorites it would be necessary to reproduce the picture of the origin and absorption of primary particles of cosmic radiation, as well as of the behavior of the secondary particles they produce in nuclear reactions with the meteorite material in bodies that are approximately spheroid in shape and irradiated isotropically by galactic cosmic rays. Only by a detailed consideration of the entire set of theoretical and experimental data on the characteristics of nuclear reactions has it been possible to build a model of the processes that are taking place, and to describe quantitatively the distribution of nuclear active particles in terms of depth in meteorites of different sizes and compositions.

By using the probabilities of the formation of isotopes we found in the experiments, we were able to obtain more accurate data on the rates of formation of the most varied of nuclear reaction products in unit time and for one particle of cosmic rays striking meteorites of different types. This resulted in solving the problem of selecting the types of meteorites best suited for studying variations in galactic cosmic rays. Included are the most widely known meteorites, the chondrites, which comprise some 80 percent of all fallen meteorites. Chondrite composition in percentage in most cases is oxygen 40, magnesium 20, iron 25, silicon 20, calcium 1.5, aluminum 1.5. Chondrites have three phases: silicate; iron; and sulfide. Characteristic of their structure is rapidly solidified spherules of silicate cemented into a matrix of nickel-iron and iron sulfide. Most chondrites are small so the nuclear reaction products they contain do not change with depth. Some 20 chondrites have fallen in the past decade, enabling us to determine the fluxes of galactic cosmic rays at different periods of the 19th and 20th cycles of solar activity and to trace the effects of 11-year modulation.

The procedural concept we have proposed is to use the known orbits of the meteorites and their speeds to determine the integral intensity of galactic cosmic rays over the section traversed by the meteorite during the lifetime of the corresponding radioisotope formed by cosmic ray nuclear reactions. Let us illustrate this by taking the example of the Pribram chondrite, which fell on 17 March 1957, the year of the maximum in the 19th cycle of solar activity.

This fall was unique in that it was possible to track the meteorite during its flight and to photograph its trajectory from several geographic points in Czechoslovakia. All characteristics of its orbit were calculated. Its aphelion was 4.1 AU, the perihelion 0.8 AE, the time of a complete revolution around the sun 3.765 years, and the change in orbital speed, as shown by the curve in Figure 6, plotted by A. N. Simonenko. The arrows on the curve indicate the ends of the sections in which there occurs the accumulation of equilibrium activity of the short-lived radioisotopes found in the meteorite before it fell on the earth, when the nuclear reactions in the meteorite material have ceased. The /16 earth's surface is protected against the action of cosmic rays by its comparatively dense atmosphere. The Pribram chondrite collided with the earth at point A, that is, prior to passage through the perihelion. As will be seen from the curve, one of the most widely known radioisotopes in chondrites, ^{22}Na, permits determination of the total flux of galactic cosmic rays during a period equal to 3.88 years, that is, for a period of time slightly longer than that required for the Pribram meteorite to make one complete revolution around the sun. The radioisotope ^{49}V provides the same determination for 1.36 years, ^{54}Mn for 1.2 years, ^{45}Ca for 0.68 years, ^{46}Sc for 0.342 years, ^{37}Ar for 0.144 years, and, finally, the one with the shortest life, ^{32}P, for 21 days prior to the meteorite's fall into the earth. All these radioisotopes can be detected in fallen meteorites if they arrive in the laboratory within 15 to 30 days after having fallen. Analysis of the data on radioisotope content in meteorites fallen between 1959 and 1969 resulted in our arriving at important conclusions with respect to variations in galactic cosmic rays during this period.

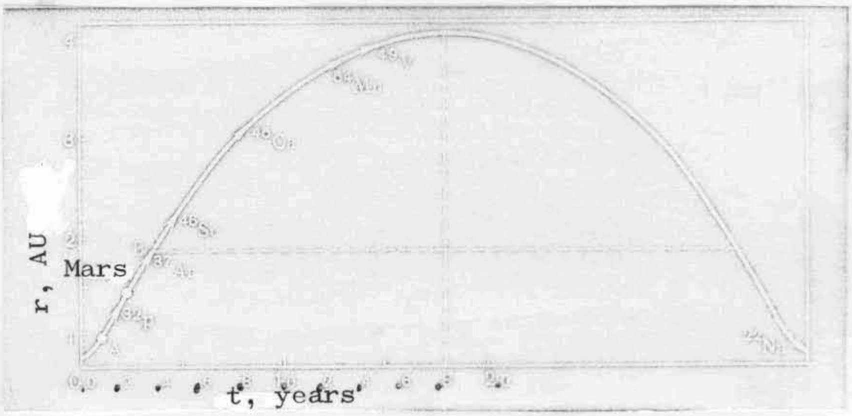

Figure 6. Diagram of the change in the distance of the meteorite Pribram from the sun during one revolution. The meteorite is considered as moving from right to left. Plotted on the abscissa is time to calculated arrival of the meteorite at perihelion. It failed to arrive because it impacted on earth at point A. Distance from the sun (in AU) is plotted on the ordinate. Point B is the suggested boundary of the region of galactic cosmic ray modulation. The arrow heads indicate the lifetime (one and one-half times the half-life) of the radioactive isotopes forming in the meteorite under the effects of the galactic cosmic rays before collision with the earth. These times have been plotted on the curve depicting the movement of the meteorite for purposes of clarity, rather than along the time line (according to A. N. Simonenko).

Meteorites are irradiated by unmodulated galactic cosmic rays throughout their orbits (see Figure 5). This conclusion is based on the constancy of the activity of ^{22}Na, and this enables us to determine the total intensity of the rays during this period in six chondrites that fell during the years of the 19th solar cycle: Pribram (17 March 1959); Hamlet (13 October 1959); Bruderheim (4 March 1960); Ekhole (31 August 1961); Peace River (31 March 1963); San Savarin (27 June 1966). The mean activity of the ^{22}Na is (90^{+11}_{-16}) decays per minute per kilogram. Using this figure, and the value calculated using the model experiments as a basis, we found that the mean flux of galactic cosmic rays with energies greater than 100 million eV/nucleon during the period of the 19th solar cycle equaled 0.41 particles/cm^2· sec· sr. This value, within the limits of error of methods used to calculate and measure activity (± 20%), is equal to the intensity of the primary cosmic rays at the boundary of the earth's atmosphere during the period of the 1965 minimum, when, practically speaking, they had not been swept here from the solar system.

The effective region of the 11-year modulation therefore is within the limits of meteorite orbits (4 AU). If the region of modulation is outside this limit, the activity of the ^{22}Na in meteorites should change in accordance with observed changes in the intensity of galactic cosmic rays at the boundary of the earth's atmosphere (see Figure 4). Its constancy uniquely delimits the modulation region.

The isotope ^{54}Mn, formed on the section from the aphelion to the earth (see Figure 6), was used to determine the upper boundary of the modulation region. Its activity in the chondrites that fell between 1960 - 1969 (Bruderheim, Ekhole, Peace River, Zaysan, San Savarin, Allende) varies over a 20 percent range that corresponds to the section AB on the curve in Figure 6, and this, simultaneously, characterizes the region in which meteorites can be irradiated by modulated cosmic rays. So the upper boundary of the 11-year modulation region is some 2 AU from the sun. This is confirmed by the data on ^{46}Sc, the activity of which begins to accumulate from the time the meteorite approaches the sun at a distance of 2.2 AU, that is, close to the upper boundary of the modulation region. It was found that the activity of the ^{46}Sc in the chondrite Bruderheim (4 March 1960) is half that in the chondrite San Savarin (27 June 1966), and this matches the change in the flux of galactic cosmic rays on the earth during those years.

The data on the isotope ^{37}Ar, which forms on the section of the orbit within the modulation region, are of interest. Its activity in the year of the solar activity maximum was higher (chondrite Hamlet, 1959) than in the year of the minimum (chondrite Baruell, 24 December 1965), although the activity of the ^{39}Ar ($T_{1/2}$ = 325 years), which did not experience the 11-year modulation, was constant in the six that fell in the period. The ^{37}Ar/^{39}Ar activity ratio, which does not depend on the size of the meteorites, decreases with decrease in solar activity, and is a minimum in 1965. These data confirm the reality of the magnetic boundary of the diffusion layer. Solar cosmic rays reflected from it make a significant contribution to the formation of ^{37}Ar. The magnetic boundary of the diffusion region is about 2 AU from the sun and its existence is what causes the 11-year variation in galactic cosmic rays. This boundary coincides with the beginning of the asteroid belt. Microasteroids vaporize upon collision and the turbulent magnetic fields are formed. The data reported at the 13th Plenary Session of COSPAR in May 1970, by W. Cocott suggest that the maximum number of microasteroids are right at 2 - 2.6 AU from the sun.

Thus, long before direct measurements by artificial space probes, the natural space probes, the meteorites, provided the possibility of determining the boundary between the solar and galactic magnetic fields and of establishing that this boundary is associated with the asteroid belt, spatially and physically. It would appear that the inner planets of the solar system (Mercury, Venus, Earth, Mars) not only differ from the out (Jupiter and others) in chemical composition and density, but that the interplanetary medium in which the outer planets are immersed has significantly different properties from those found in the medium surrounding the planets of the earth group.

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